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Electrostatics and kinetics of 2D electrons in lateral superlattices on vicinal planes

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Abstract. The potential of one-dimensional lateral superlattice screened by two-dimensional electron gas located in close proximity is found. The periodic potential created by the superlattice effects on the kinetic and optical properties of the electron system. Magnetorefectance, Faraday rotation angle and ellipticity of the reflected electromagnetic field are calculated.

Introduction

One of possible ways to fabricate short periodic lateral superlattice (SL) is segregation of charged impurities on vicinal planes of crystals (see Fig. 1). The terraced interface of a heterojunction is populated by donors nonuniformly. The latters tend to aggregate themselves at the edges of the terraces forming the chains of positive charges. As a result, the 2D electrons residing close to the interface "see" a one-dimensional periodic potential $V(x)$ with the period a determined by the angle of disorientation of the vicinal plane (see e.g. [1, 2, 3]).

Usually the potential $V(x)$ is represented by its Fourier components $V^{(r)}$ which are just given parameters of the theory. In the present paper we, first of all, calculate the potential $V(x)$ accounting for the screening effects in 2D electron gas. Then we consider magneto-optical phenomena in 1D lateral SL.

1 Screened potential of 1D SL

Consider a periodic set of charged filaments parallel to the y -axis and placed in the plane $z = 0$. The linear density of charge at each filament is ξ . In the plane $z = -\Delta$ we have strongly degenerate 2D electron gas. The problem is to find the self-consistent potential $V(x)$ and areal density of electrons $\sigma(x)$ in the plane $z = -\Delta$.

The electrostatic problem with *finite* screening is, generally speaking, nonlinear because the density of charge depends on the potential. However, a lucky exception is the Thomas–Fermi limit for 2D electron gas. Indeed, the areal density of 2D electrons $n(\mathbf{r})$ is given by ($T \rightarrow 0$)

$$n(\mathbf{r}) = \frac{m^*}{\pi \hbar^2} [\mu + e\varphi(\mathbf{r})] \vartheta[\mu + e\varphi(\mathbf{r})], \quad (1)$$

where $\vartheta(t)$ is the Heaviside step function, μ is the chemical potential. For a single charged filament placed at the distance Δ above the 2D degenerate electron gas one has

$$\varphi(x; z = -\Delta) = -2\xi e^{\kappa\Delta} \operatorname{Re}\{e^{-i\kappa x} Ei[\kappa(x - i\Delta)]\}, \quad (2)$$

where $Ei(t)$ is the exponential integral. After summation over all the filaments arranged in the periodic set with the period a we arrive eventually at the formula for the potential of SL

$$V(x) = \frac{\pi\xi}{\kappa a} \int_0^\infty dz \frac{e^{-z} \sinh[2\pi(\Delta + z/\kappa)/a]}{\cosh[2\pi(\Delta + z/\kappa)/a] - \cos^2(\pi x/a)}. \quad (3)$$

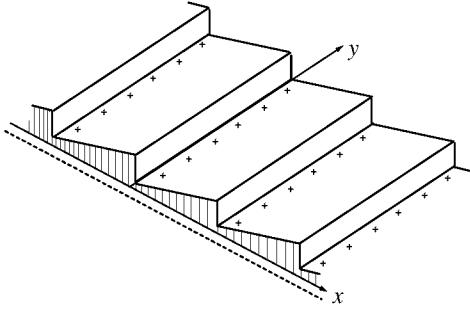


Fig. 1. Two-dimensional electron gas at a vicinal surface; + charged donors, – electrons.

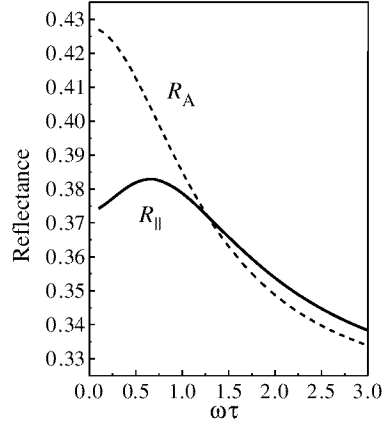


Fig. 2. Frequency dependence of the reflectance at $B = 0$. Here and in the following figures solid (dash) line corresponds to $R_{||}$ (R_{\perp}).

The Fourier components $V^{(r)}$ of the potential (3) can be calculated analytically. For example,

$$V^{(1)} = \frac{\pi \xi}{\kappa a} \frac{e^{-2\pi \Delta/a}}{1 + 2\pi/\kappa a}.$$

2 Dynamic conductivity of 1D SL

In this section the expressions for components of a dynamic magnetoconductivity tensor $\sigma(\omega, \mathbf{B})$ of 1D lateral superlattice are derived. The linearized kinetic equation for a degenerate ($T = 0$ K) electron system subject to a laterally modulating potential $V(x)$, a constant uniform magnetic field \mathbf{B} (axis z) and a microwave field $\mathbf{E}(t) = Re(\mathbf{E}_\omega e^{-i\omega t})$ reads:

$$\begin{aligned} \hat{\mathcal{L}}_\omega \chi \equiv & \left[v(x) \cos \varphi \frac{\partial}{\partial x} + \left(\frac{\partial v}{\partial x} \sin \varphi + \omega_c \right) \frac{\partial}{\partial \varphi} \right. \\ & \left. + \frac{1}{\tau} \left(1 - \int_0^{2\pi} \frac{d\varphi}{2\pi} \right) - i\omega \right] \chi = -e \mathbf{E}_\omega \mathbf{u} v(x). \end{aligned} \quad (4)$$

Here \mathbf{u} is the unit vector ($\mathbf{u} = (\cos \varphi, \sin \varphi)$), $v(x) = v_F \sqrt{1 + eV(x)/E_F}$ is the magnitude of the electron velocity (v_F is the Fermi velocity), $\omega_c = eB/m^*c$ is the cyclotron frequency, τ is the relaxation time (assumed to be constant).

We assume the lateral potential $V(x)$ to be weak that allows one to solve Eq. (4) perturbatively. To the lowest order in V we come to the following expression for magnetoconductivity:

$$\sigma_{ij}(\omega, \mathbf{B}) = \frac{\sigma_0 \eta}{\eta^2 + \gamma^2} \left\{ d_{ij} - \frac{\eta d_{ix} d_{xj} q^2 l^2}{2(\eta^2 + \gamma^2)} \sum_{r=-\infty}^{\infty} r^2 \frac{|eV^{(r)}|^2}{E_F^2} \cdot \frac{S(rq v_F / \omega_c)}{1 - S(rq v_F / \omega_c)} \right\} \quad (5)$$

$$S(z) = \eta \sum_{n=-\infty}^{\infty} \frac{J_n^2(z)}{n^2 \gamma^2 + \eta^2}.$$

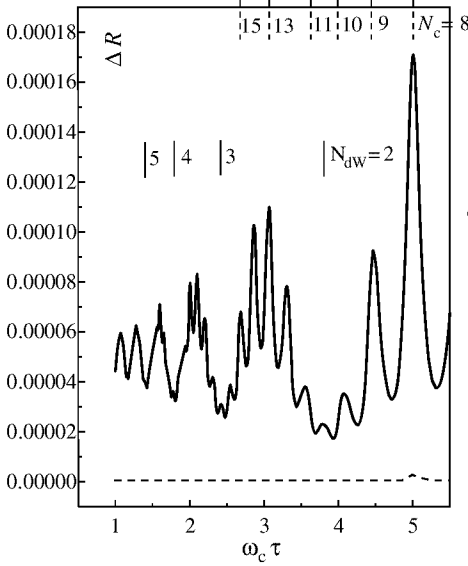


Fig. 3. Magnetic field dependence of $\Delta R(B) = R(B) - R^{(0)}(B)$ for $\omega\tau = 40$. Solid ticks indicate the positions of dynamic Weiss oscillations followed from Eq. (6), dashed ticks mark CR harmonics ($\omega = N_c\omega_c$).

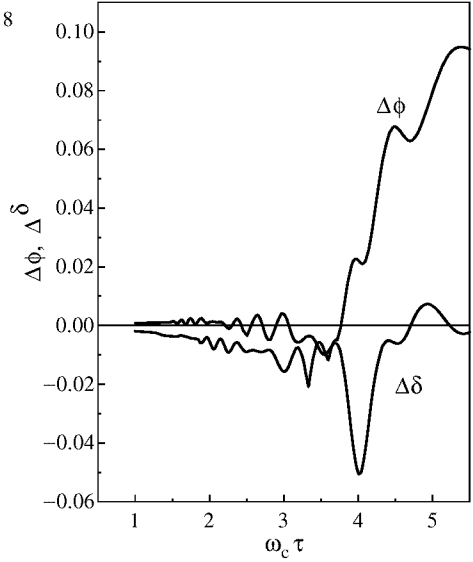


Fig. 4. Magnetic field dependence of the Faraday rotation angle ϕ and ellipticity δ for $\omega\tau = 4$.

Here $q = 2\pi/a$, $\sigma_0 = N_s e^2 \tau / m^*$, $d_{xx} = d_{yy} = 1$, $d_{yx} = -d_{xy} = \gamma / \eta$, $\gamma = \omega_c \tau$, $\eta = 1 - i\omega\tau$, $l = v_F \tau$ is the free path length, $J_n(z)$ are Bessel functions.

3 Magnetorefectance and Faraday effect

The expressions (5),(6) allows us to find the reflectance R , Faraday rotation angle ϕ and ellipticity δ .

The results of numerical computations are depicted in Figs. 2–4. For calculations the following parameters have been used: $\mu = 5 \cdot 10^4 \text{ cm}^2/\text{V}\cdot\text{s}$ ($\tau = 1.9 \text{ ps}$), $m^* = 0.067m_0$, $N_s = 4 \cdot 10^{11} \text{ cm}^{-2}$ ($E_F = 14.29 \text{ meV}$, $v_F = 2.74 \cdot 10^7 \text{ cm/s}$), $a_0^* = 10.12 \text{ nm}$, $a = 32 \text{ nm}$, $\Delta = 75 \text{ A}$, $\xi = 2 \cdot 10^5 \text{ e/cm}$, $n = 3.58f$. At $B = 0$ we plot R_{\parallel} and R_{\perp} as functions of the frequency ω (Fig. 2). For y -polarized incident wave we have conventional monotonic Drude behavior $R_{\perp} \equiv R^{(0)}(\omega)$; we denote by $R^{(0)}$ the reflectance of the unmodulated system. However for x -polarized case the effect of lateral SL results in the curve $R_{\parallel}(\omega)$ with maximum at $\omega\tau \sim 1$. In the magnetic field the results essentially depend on the interplay of parameters ω , $\omega_0 = 2\pi v_F/a$ and τ . In the frequency region $1 \ll \omega\tau \ll \omega_0\tau$ (for chosen parameters $\omega_0\tau = 72.4$), a picture of beatings occurs: the envelope function connected with the cyclotron resonance (CR) and its harmonics modulates conventional Weiss oscillations. An example of $R(B)$ corresponding to the case $\omega \lesssim \omega_0$ ($\omega\tau = 40$) is shown in Fig. 3. Under given frequency CR harmonics are modulated by the envelope function with minima which obey the relation

$$2 \frac{v_F}{a} \Phi \left(\frac{\omega}{\omega_0} \right) = \omega_c \left(N_{dw} - \frac{1}{4} \right), \quad (6)$$

where $\Phi(x) = \sqrt{1-x^2} - x \arctan(1/x^2 - 1)$, $N_{dW} = 1, 2 \dots$. Here we have the manifestation of so called dynamic Weiss oscillations. The possibility of observation of Weiss-type oscillations in dynamic regime has been predicted in [24]. At $\omega > \omega_0$ only CR harmonics with the exponential envelope function are left (no Weiss oscillations).

Similar oscillation behavior due to the periodic lateral potential can be also observed in other magneto-optical values, as a transmittance, Faraday rotation angle etc. B -dependence of the Faraday rotation angle and ellipticity in a reflected electromagnetic wave is shown in Fig. 4. In the accepted scale the results for two polarizations coincide very closely.

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